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Title Page:

Title: Empirical Study on the Environmental Pressure versus Economic Growth in China during 1991-2012

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Abstract:

Abstract: Since adoption of the policy of reform and opening-up in 1978, China has achieved spectacular success in economic growth, which mainly driven by abundant consumption of natural resources but resulted in serious environmental problems. Based on Emergy approach and Rescaled Range analysis, this paper aims to examine the decoupling condition in economic growth nexus environmental pressureboth at specific and aggregate level and track the changing trend and the corresponding socio-economic cost in decoupling process. The results show that: the decoupling performance of waste emission (includes waste water, SO_2 and solid waste) is better than energy consumption at a specific level which implies that the policies focused on end-of-pipe treatment has been succeeded in meeting the targets of emission reduction.But at aggregate level, the situation is opposite which suggest that China need more efforts in life-cycle management; The weak decoupling condition of resource use and waste water discharge may continue in the future, so as the strong decoupling condition of SO_2 and solid waste, but for the aggregate environmental pressure induced by waste emission, the decoupling performance may be getting worse in the future; The investment cost of decoupling increased, whilst the job-cost of decoupling decreased; The decoupling performance can be influenced by environmental policies substantially, such as the polices of circular economy, rigorous emission reduction and waste recycling which have brought about the strong decoupling SO_2 emission and solid waste discharge from economic growth, whereas the less rigorous policies on resource exploitation and waste water discharge didn't achieve the same result. Therefore, China needsto intensify the unity among various environmental policies.

Highlights

- The decoupling performance of waste emission is better than energy consumption at a specific level, but at aggregate level, the situation is opposite.
- The weak decoupling condition of resource use and waste water discharge may continue in the future, so as the strong decoupling condition of SO_2 and solid waste, but for the decoupling performance of the aggregate environmental pressure induced by waste emission may be getting worse in the future.
- The decoupling performance can be influenced by environmental policies substantially
- The investment cost of decoupling increased, whilst the job-cost of decoupling decreased

Keywords: Emergy; Decoupling Analysis; Social Metabolism; Human-Environmental Interactions; China

Text

1. Introduction

China has experienced spectacular economic growth mainly indicated as gross domestic product (GDP) which has increased more than 22-fold since 1978. The remarkable growthhas made China the second largest economy,and also the largest energy consumer(Zhang et al. , 2011a), the biggest energy-related CO_2emitter(IEA, 2006), the largest solid waste generator(Chen et al. , 2014) and the largest single contributor to global SO_2 emission(Li et al. , 2013) in the world. Therefore, China's economic growth "coupled" with the increase in resources consumption andwaste emission. The couplingbetween resources consumption and economic growth as well as pollution emissions are central to the debates(Xue et al. , 2010). China's serious environmental challenges call for disclosing the relationship between economic growth and environmental pressure, which is important for achieving environmental sustainability for both China and the world (Liang et al. , 2013, Liu and Diamond, 2008, Liu and Diamond, 2005). It is generally agreed that resources use and waste emission should be "decoupled" from economic growth(Wang et al. , 2013).

Currently, decoupling has been defined by several organizations and academic groups, such as decoupling is "breaking the link between environmental bad and economic goods " by Organization for Economic Co-operation and Development (OECD) (OECD, 2002);is "the reduction of the negative environmental impacts generated by the use of natural resources in a growing economy" by European Union (EU)(Mudgal et al. , 2010), and is "reducing the amount of resources used to produce economic growth and delinking economic development from environmental deterioration" by United Nation Environmental Program (UNEP)(UNEP, 2011). Two main kinds of decoupling are in general taken into account, definedas relative and absolute decoupling. Relative decoupling refers toa decrease of emissions intensity per unit of economic output.Absolute decoupling refers to an overall decrease of emissions asGDP increases(Andreoni and Galmarini, 2012).Thus, decoupling has beenthe overall goal of environmental sustainability(Kovanda and Hak, 2007), and the process of decoupling is generally considered to be crucial for sustainable development strategies such as the *factor 4* or *factor 10* in resource use(Hanssen et al. , 2007, Pretty, 2013, Reijnders, 1998, Weizsäcker et al. , 1997).For example, decoupling has been proposed as one of five inter-linked objectives for enhancing cost-effective and operational environmental policy of OECDin the context of sustainable developmentfor the first decade of the 21^{st} century (Moldan et al. , 2012, OECD, 2001, Wang, Hashimoto, 2013).

Decouplingwas first introduced to analysis the nexus between industrial materials and energy and economic growth in advanced countries(Marin and Mazzanti, 2013). In 1990s, researches on decoupling wereextended to air pollutants and greenhouse gasemissions, andEnvironmental Kuznets Curve(*EKC*) hypothesis was proposed to elaborate the relationship between pollution and economicgrowth, which was based on general reasoning around relative orabsolute delinking in income–environment dynamics relationships(Grossman and Krueger, 1995, Marin and Mazzanti, 2013).

To date, many differentmethods and indicators have been used to estimate the degree of decoupling (Tapio, 2005, Van Caneghem et al. , 2010, Wang, Hashimoto, 2013). There are two main indicators for quantifying the decoupling degree: one is the decoupling factor introduced by the OECD(OECD, 2002); another one is elasticity measured by the ratio of change in environment indicator to the percent change in economic indicator(Tapio, 2005). The two indicators have been used successfully in decoupling forresource use, energy consumption, and waste emissionboth in industrialized countries(Andreoni and Galmarini, 2012, Bringezu et al. , 2004, Gan et al. , 2013, Jorgenson and Clark, 2012, Kovanda et al. , 2008, Steinberger et al. , 2013, Van Caneghem, Block, 2010, Wang, Hashimoto, 2013) and China (Liang, Liu, 2013, Yu et al. , 2013, Zhang and Wang, 2013, Zhang, 2000).Previous studies mostly focused on the particular source of environmental pressure, and only few studies conducted decoupling analysis at aggregate level based on Material Flow Analysis (MFA) framework. However, the MFA-based analysis has placed emphasis on the weight (quantities) of resource flows and ignored the varied qualities of material flows. Moreover, compare with numerous case studies on decoupling in the past, few studies focused on exploring the development trend of decoupling degree. This might be due to the non-linear characteristic of decoupling degree dynamics in long time series(Zhang et al. , 2014a), which made it unable to simulate the trend of decoupling degreeby usinglinear regression analysis. And, some research havebeen done to investigate the social - economic cost for sustaining decoupling process. Therefore, a set of unified indicators should be developed and employed for advancing the current studies. In this study, we investigated the decoupling of environmental pressure from economic growth in China during 1991-2012, not only from the perspective of the particular source of environmental pressure (specific level), such as energy consumption, waste water discharge, SO_2 emission and solid waste discharge, but also the aggregate environmental indicators based on emergy analysis (aggregate level), which is a technique of quantitative analysis that determines the values of resources, services and commodities in a common unit of solar energy, which allows all resources to be compared on a fair basis and thus can overcome the limits of MFA-based analysis(Huang et al. , 2006) and provides strong and consistent evidence of the increasing consumption of resources in most economies, even in those economies that have focused their policies on dematerializing economic growth(Hoang, 2014, Zhang et al. , 2014b). The paper also analyzed the trend of decoupling degree based on Rescaled Range Analysis (R/S) method andsocio-economic costs formeeting the goal of decoupling. Section 2 in this paper presents the methodology applied in this research, and thensection 3 presents the results, followed by section 4 focusing on the policy implications anddiscussions.

2. Methods and Data

2.1 decoupling

The definition of decoupling environmental pressures (E) from economic growth (take GDP for example) is shown as in Figure 1(Tapio, 2005). Decoupling status could be estimated by the GDP elasticity values of environmental pressure which shows in Equation (1):

$$\text{GDP elasticity of E} = \%\Delta E/\%\Delta GDP \qquad (1) \qquad (1)$$

When using economic output per capita as the X-axis and environmental impact as the Y-axis, eight logical possibilities can be distinguished. In order to not over-interpret slight changes as significant, a ±20% variation of the elasticity values around 1.0 (0.8–1.2) is still regarded as coupling (Chen, Pang, 2014, Tapio, 2005). Compared to this diagram, actually, our results fell in the right part, which is indicated as zone 1 to zone 4 in Figure 1.

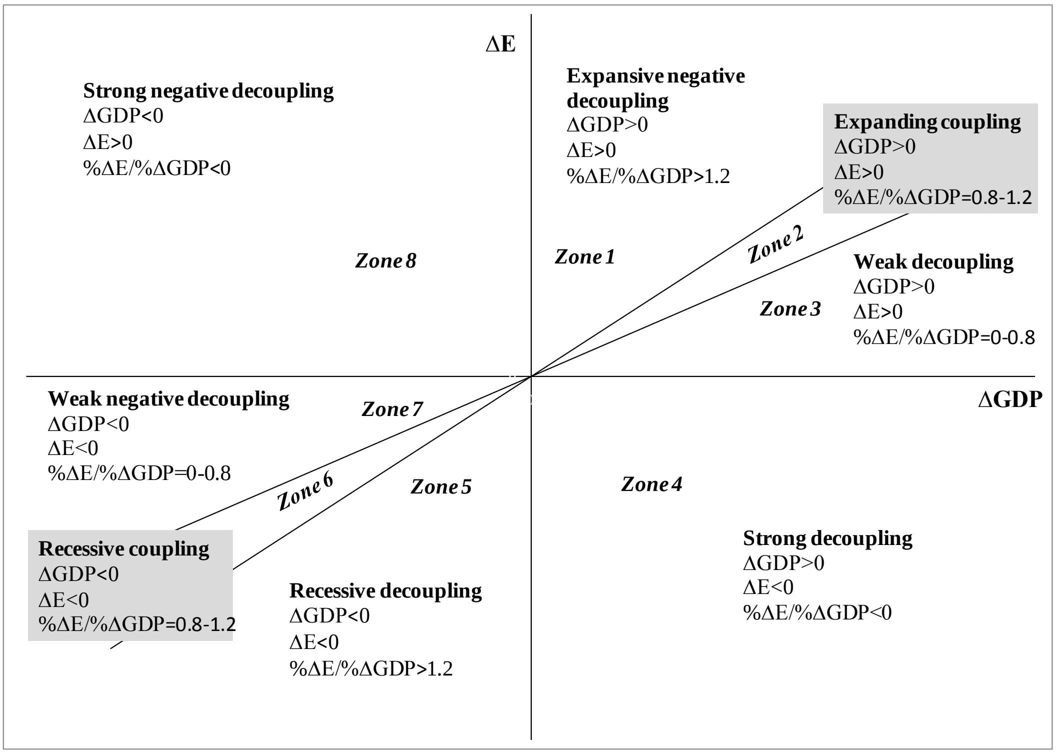

Fig. 1. Degree of coupling and decoupling zones (Tapio, 2005)

2.2 Emergy analysis

Emergy analysis is an environmental accounting method, which considers the energy system as a thermodynamics of an open system, to characterize all natural resources, capitals and services in equivalents of solar energy (i.e., how much emergy would be required to provide products and services if the solar radiation were the only input) (Brown and Ulgiati, 2011, Geng et al. , 2013, Zhang et al. , 2011b)and thus to evaluate the contributory value of different material flow to the ecological economic system (Mu et al. , 2011, Odum and Peterson, 1996). Generally, the unit of emergy analysis is solar embodied joules, abbreviated *sej*, and the key parameter is the emergy transformity (*Trf.*). The transformity of solar radiation is assumed equal to one by definition (1.0 sej/J), while the transformities of all of the other materials, energy and services are calculated based on their convergence patterns through the biosphere hierarchy. The value of the certain emergy transformityis from the corresponding references: (a)(Cuadra and Rydberg, 2006), (b)(Lan, 2002), (c)(Brown and Ulgiati, 2010), (d)(Bastianoni et al. , 2009), (e)(Riposo, 2008), (f)(Lan and Odum, 1994), (g)(Brandt-Williams, 2001), (h)(Brown et al. , 2011), (i)(Zhang et al. , 2009), and (j)(Vega-Azamar et al. , 2013)as shown in Table 1. The major steps of emergy analysis include identifying the system boundary, collecting eco-economic data, establishing emergy flow accounting, calculating a set of indices and ratios and using them to conduct the analysis.

Because our research mainly focused on the decoupling of environmental pressures induced by resources consumption and wastes emission, only two main economic activities which are agricultural and industrial activities and three main wastes include waste water, waste gas and solid waste were taken in count in the emergy analysis. The components of emergy accounting for resource consumption in agricultural sector and industrial sector are shown in Table 1. The other non-renewable resources, such as mineral resources, were not considered due to the shortage of database. The emergy accounting is simplified as three aspectsconsisting of non-renewable resources (*NRR*) consumption in agricultural system, energy consumption (*ECI*) in industrial activities, and waste emissions (*W*). Based on standard emergy transformity, the emergy accounting for *NRR*, *ECI* and *W* in 2012 are given in Table 1. The paper applied all the indicators in Table 1 to conduct the Emergy-based decoupling analysis for aggregate environmental pressure and the cost analysis of decoupling in China.

Table 1

Raw indicators used for emergy analysis in China of year 2012

Note Items	Unit	Raw data	Trf. (sej/unit)	Ref	Emergy (sej)
Non-renewable resources of agriculture					
Nitrogenous Fertilizer	*Kg*	2.40E+10	6.62E+12	a	1.59E+23
Phosphate Fertilizer	*g*	8.29E+12	9.35E+09	a	7.75E+22
Potash Fertilizer	*g*	6.18E+12	9.32E+08	a	5.76E+21
Compound Fertilizer	*g*	1.99E+13	2.80E+09	b	5.57E+22
Coal	*J*	5.17E+17	9.10E+04	c	4.71E+22
Coke	*J*	1.63E+16	6.71E+04	c	1.10E+21
Gasoline	*g*	1.93E+12	2.92E+09	d	5.63E+21
Diesel oil	*g*	1.34E+13	2.83E+09	d	3.78E+22
Kerosene	*J*	1.40E+14	5.50E+05	d	7.72E+19
Fuel oil	*g*	1.98E+10	2.66E+09	d	5.27E+19
Electricity for agri-production	*J*	3.65E+17	1.74E+05	e	6.34E+22
Pesticide	*g*	1.81E+12	1.60E+09	f	2.89E+21
Plastic Membrane	*g*	2.38E+12	3.20E+09	g	7.63E+21
Total Non-renewable resources (EmNRR)					**4.64E+23**
Industrial Energy Consumption					
Raw Coal	*J*	1.26E+19	9.10E+04	c	1.15E+24
Washed Coal	*J*	7.07E+17	9.10E+04	c	6.44E+22
Other Washed Coal	*J*	5.59E+17	9.10E+04	c	5.09E+22
Briquette	*J*	1.03E+17	9.10E+04	c	9.33E+21
Coke	*J*	1.11E+19	9.10E+04	c	7.47E+23
Coke Oven Gas	*J*	9.25E+14	1.71E+05	h	1.58E+20
Other Gas	*J*	2.15E+15	1.71E+05	h	3.67E+20
Other Coking Products	*J*	2.23E+17	9.10E+04	d	2.03E+22
Crude Oil	*J*	2.32E+17	1.48E+05	h	3.44E+22
Gasoline	*g*	5.81E+12	2.92E+09	c	1.70E+22
Kerosene	*J*	1.38E+16	5.50E+05	c	7.60E+21
Diesel Oil	*g*	1.68E+13	2.83E+09	c	4.76E+22
Fuel Oil	*g*	6.31E+12	2.66E+09	c	1.68E+22
LPG	*g*	4.63E+12	3.11E+09	c	1.44E+22

Refinery Gas	*g*	1.28E+13	3.11E+09	c	4.00E+22
Natural Gas	*J*	8.39E+14	1.71E+05	c	1.43E+20
Electricity	*J*	1.20E+19	1.74E+05	e	2.09E+24
Total Emergy of Industrial Energy Consumption (EmECI)					**4.31E+24**
Total Emergy of Resource Consumption (EmTRC)=EmNRR+EmECI					**4.77E+24**
Waste emission					
Waste Water	*J*	3.42E+17	6.66E+05	i	2.28E+23
Waste Gas	m^3	6.34E+13	6.68E+10	b	4.25E+24
Solid Waste	*J*	9.13E+14	1.80E+06	j	1.64E+21
Total Waste Emergy (EmTW)					**4.48E+24**

The raw indicators for decoupling analysis include final energy consumption, wastewater discharge, SO_2 emission, solid waste discharge, *EmTRC*, *EmTW* and the real GDP of China during 1991-2012. The first four indicators represent the particular source of environmental pressure; the *EmTRC* and *EmTW* represent aggregate environmental pressure induced by non-renewable resource use and waste emission; and the real GDP, which measured as real GDP value in purchase power parity (at constant price in 1978) to eliminate the impact of price factors on the data, represent the economic growth. For ease of comparison, all indicators were standardized such that indicators value for 1991 were set to equal to 100, i.e., 1991=100 (Figure 2). All the raw social, economicand environmental data in the paper are extracted from the annual China Statistical Yearbook(NBS, 1992-2013b), China Environment Yearbook(MEP, 1992-2013) and China Energy Statistical Yearbook(NBS, 1992-2013a) Table 1.

3. Results

3.1 Decoupling Analysis

Along with the rapid economic development in China, the amount of final energy consumption, waste water discharge and SO_2 emission increased 3.40, 2.03 and 1.31 times respectively since 1991. However, due to the implementation a series of regulations and policies for solid waste management, such as the Law of the People's Republic of China on The Prevention and Control of Environmental Pollution by Solid Waste and the Law on Circular Economy Promotion(Chen, Pang, 2014, Xue et al. , 2011), the solid waste discharge generally showed decreasing trend during 1991-2012 except the period of 1997-1998 and the amount decreased by 12.84% (Figure 2). The reason for the sudden increase in solid waste in 1998 is that the amount of industrial solid waste generation in the mining and quarrying sector rapidly increased from 311.9 million tons in 1997 to 408.23 million tons in 1998(Chen, Pang, 2014).

The changes in the gap between the trajectory of the real GDP and environmental indicators in the time series graph can be used to identify the general decoupling situation. The gap between the trajectory of the real GDP and other indicators except for *EmTW*in Figure 2 over the investigated period was generally enlarging which indicates the decoupling, at least relative decoupling of environmental pressure from economic growth happened.Overall speaking, with regards to final energy consumption, wastewater discharge and *EmTRC*, their growth rate was smaller than GDP's which suggests that energy consumption, waste water and aggregate resource use decoupled from economic growth relatively. The amount of $SO_2$was increased first (1991-2006) and then decreased (2006-2012) which indicates that the relative decoupling of SO_2happened during 1991-2006 and absolute decoupling happened during 2006-2012. The absolute decoupling of solid waste discharge was found in the whole investigated period.As for the total waste emergy (*EmTW*), which indicates the aggregated environmental pressure induced by waste emission, the gap between the change trajectory of *EmTW* and the real GDP was enlarging slowly at first, however, the gap remained stable after 1999 and even narrowed in some years. The resultsindicate that the decoupling situation of aggregate environmental pressure induced by waste emission is worse than resource consumption.

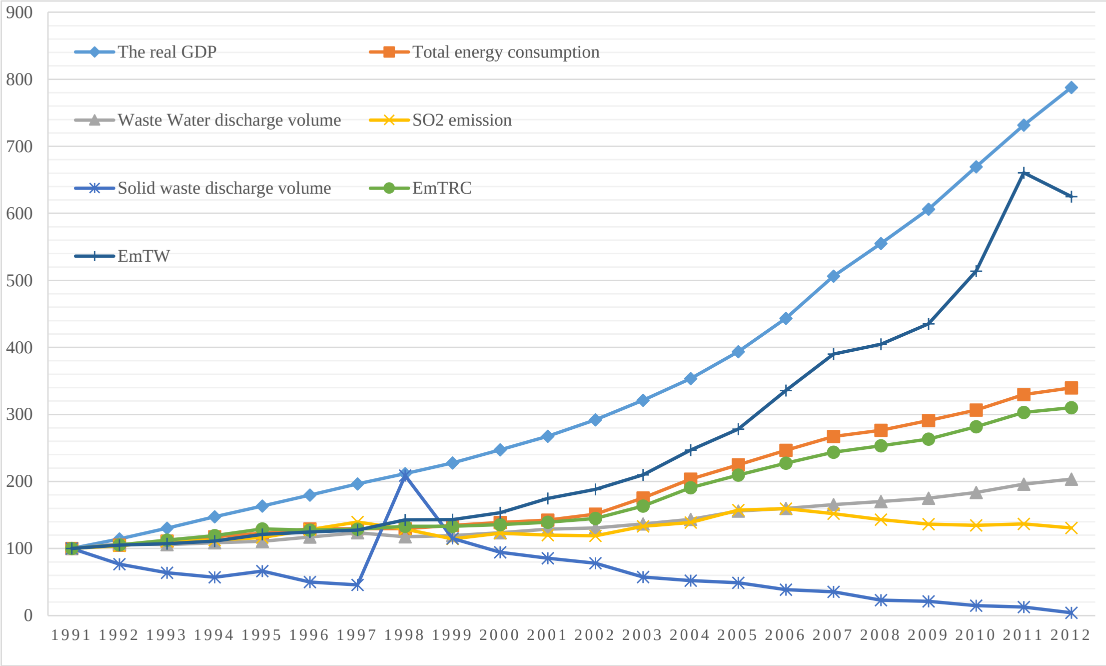

Fig. 2. Historical evolution of economic growth, energy consumption and waste emission of China (year 1991=100).

3.1.1 Decoupling of Particular sources of environmental pressure

In order to examine the decoupling condition and its time variation, the whole-observation period of 1991-2012 was therefore broken into 21 periods, and the decoupling status of final energy consumption, waste water discharge, SO_2 emission and solid waste discharge for each period based on Tapio's method (Figure 3-6) were presented.

The time variations in the decoupling of the final energy consumption in investigated periods showed a disordered state (Figure 3). Weak decoupling of energy consumption happened in China in the each period during 1991-2002 and the last period (2011-2012). And non-decoupling of energy emerged in each periods during 2002-2006, and 2010-2011, in which the non-decoupling in periods 2002-2003 and 2003-2004 shows expansive negative decoupling, and others show expanding coupling relationship.Energy reducing has been taken as the basic state policy in China for more than 20 years, and the energy consumption per capita (energy intensity) reduced an average of 5% annually from 1980-2002(Price et al. , 2011, Yuan et al. , 2011). However, with a dramatic reversal of the historical evolution of energy intensity, the energy use per capital in China increased an average of 5% per year during the period of 2002-2006 which led to the emergence of non-decoupling in energy consumption in that period.In order toreduce the energy intensity constantly, Chinese government introduced the Energy Saving and Emission Reduction (*ESER*)target in the China's 11thYear Plan (2006-2010) which is to reduce the energy intensity by 20% in five years. And China has implemented a series policies and program to fulfill the national goal of energy saving and also turned around the decoupling status of energy use during the each period of 2006-2012 except the last period. China, like most of the other developing country, is still on the transforming phase from primary industrialization to modern industrialization, the situation of fast economic growth triggered by vast volume energy consumption still exists at present and would last for years because of effects of path dependent.

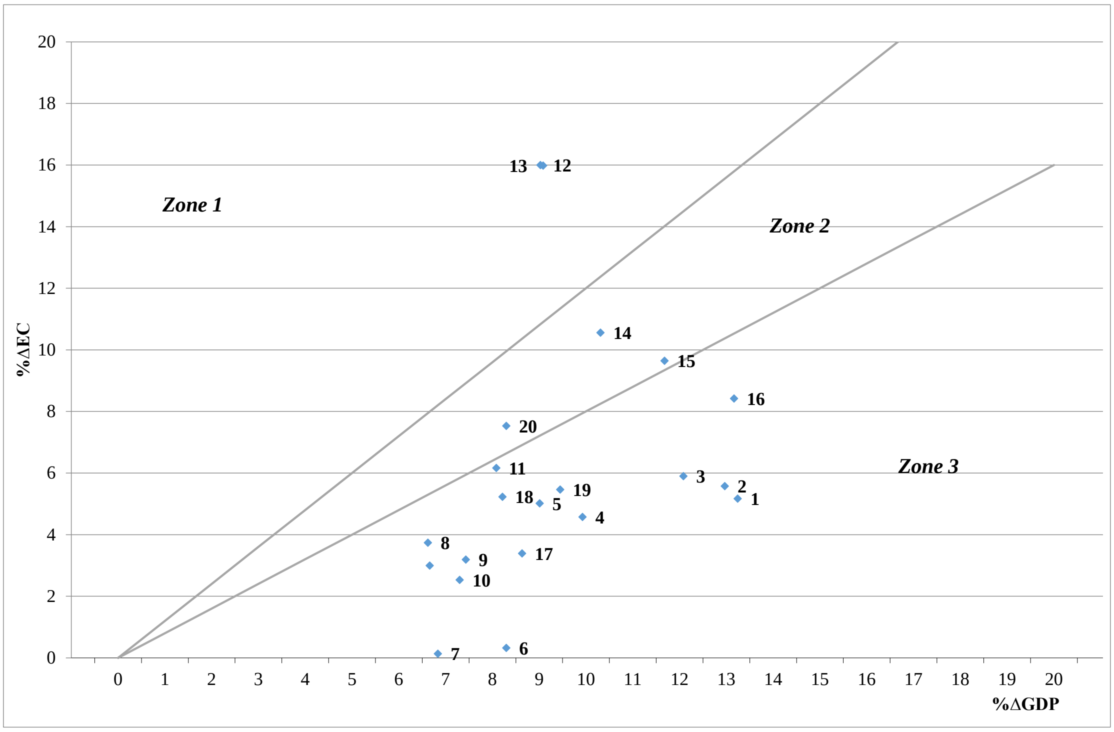

Fig. 3. Decoupling index between GDP and energy consumption in China.**[**Notes: Numbers represent period: 1 indicates 1991-1992; 2 indicates 1992-1992; 3 indicates 1993-1994, ..., and 21 indicates 2011-2012]

With regard to wastewater, as depicted in figure 4, two points of 2004-2005 and 2010-2011 located in the expanding decoupling area, two points of 1992-1993 and 1997-1998 located in the strong decoupling area, and other seventeen points located in the weak decoupling area. The weak decoupling of wastewater emission happened in most of periods (account for 81%) due to the increasing and substantial discharge of wastewater led by rapid urbanization and industrialization. The results indicate that China is facing the serious problem of wastewater treatment and need more stringent discharge standards and efforts to improve the waste water recycling level both in industrial and municipal level(Geng et al. , 2014, Wang, 2012).

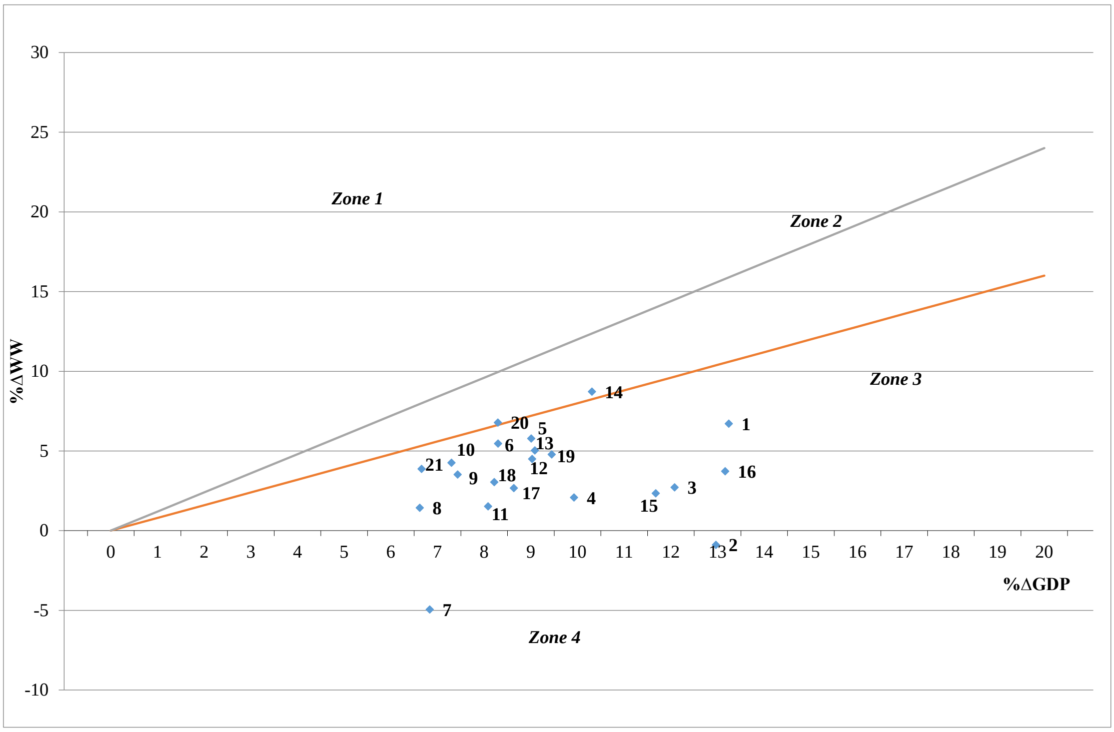

Fig. 4. Decoupling index between GDP and waste water discharge in China. [Notes: the same as shown in Figure 3]

In the term of SO_2 emission, five points were in the non-decoupling area in which two points of 2002-2003 and 2004-2005 were in the expansive negative decoupling area and three points of 1995-1996, 1996-1997 and 1999-2000 were in the expanding coupling area (Figure 5). Sixteen points were in the decoupling area, in which seven points of 1991-1992, 1992-2993, 1993-1994, 1994-1995, 2003-2004, 2005-2006, and 2010-2011 were in the weak decoupling and nine points of 1997-1998, 1998-1999, 2000-2001, 2001-2002, 2006-2007, 2007-2008, 2008-2009, 2009-2010 and 2011-2012 were in the strong decoupling area (Figure 5). The lower increase rates of SO_2 emission and real GDP (Figure 2) were result in the weak decoupling happened in 1991-1995. However, due to the fast industrialization which has been considered as main source of SO2 emission (industrial SO_2 emission account for above 80%)(Wei et al. , 2012), the coal-based energy structure and the failure of the early policies on reducing SO_2 emission (Schreifels et al. , 2012), the weak decoupling and non-decoupling of SO_2mostly happened in the various periods from 1996-2005. In order to reduce SO_2 substantially and fulfill the emission reduction goal in 11th Five-year Plan period, the Chinese government adapted a number of policies and introduced new instrument which has made the SO_2emission decline by 14% in 11th Five-year period.Thus, most of strong decoupling of SO_2 happened after 2005. Therefore, we can conclude that the decoupling condition can be influenced substantially by the changes in the environmental policies which also was proved by Wang (2013).

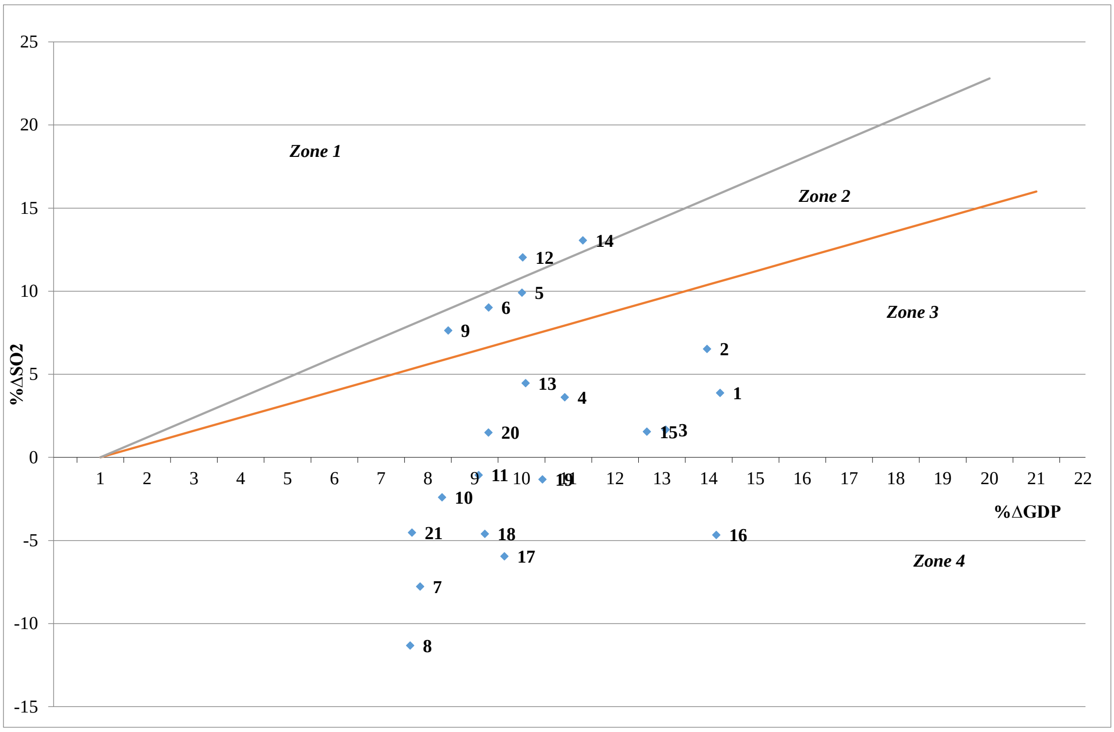

Fig. 5. Decoupling index between GDP and SO_2 emission in China. [Notes: the same as shown in Figure 3]

The decoupling of solid waste in China has achieved since 1991(Figure 6), and the most of periods showed strong decoupling from economic growth except the weakdecoupling point of 1994-1995 and non-decoupling point of 1997-1998. In figure 4, a point (7.833, 355.003) of 1997-1998 is beyond the figure area because the amount of industrial solid waste generation in the mining and quarrying sector rapidly increased from 311.9 million tons in 1997 to 408.23 million tons in 1998. The strong decoupling of solid waste owns to the serious of rigorous regulations and policies for solid waste management issued by Chinese government, such as the Law of People's Republic of China on the Prevention of Environmental pollution, which is the main legislation specifically pertaining to solid waste management and pollution control, the Law of the People's Republic of China on The Prevention and Control of Environmental Pollution by Solid Waste issued in 1996 and amended in 2004, the Law on Circular Economy Promotion issued in 2009, and has established a legal framework on SW reduction, reuse and recycling (so called *3Rs*) *et al.*The investment in solid waste treatment equipment and infrastructure increased 7.94 times, and over 3.95 times more solid waste was treated or disposed of safely from 1991–2012.

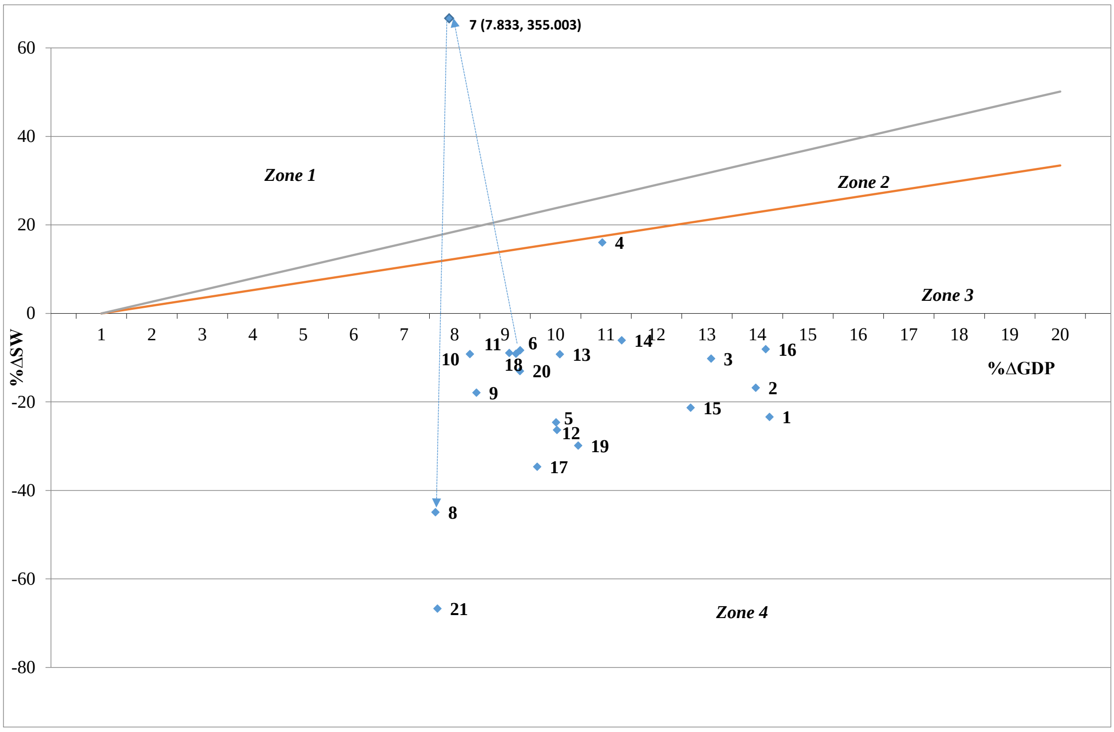

Fig. 6. Decoupling index between GDP and solid waste discharge in China. [Notes: the same as shown in Figure 3]

3.1.2 Emergy-based decoupling analysis

The emergy-based decoupling analysis was conducted by using the decoupling method and emergy analysis resultsin section 2.1 and 2.2 to investigate the decoupling condition of comprehensive environmental pressure induced by resource use and waste emission which indicated by *EmTRC* and *EmTW* respectively. As for the *EmTRC* (Figure 7), two points of 2002-2003 and 2003-2004 located in the expansive negative decoupling area, and three points of 1994-1995, 2004-2005 and 2010-2011 located in the expanding coupling area. The others were in the weak decoupling area except the point of 1998-1999 which were in the negative decoupling area. The decoupling condition of *EmTRC* is similar to the energy consumption (Figure 3) which indicate that energy consumption is the main source of environmental pressure generated by resource use.

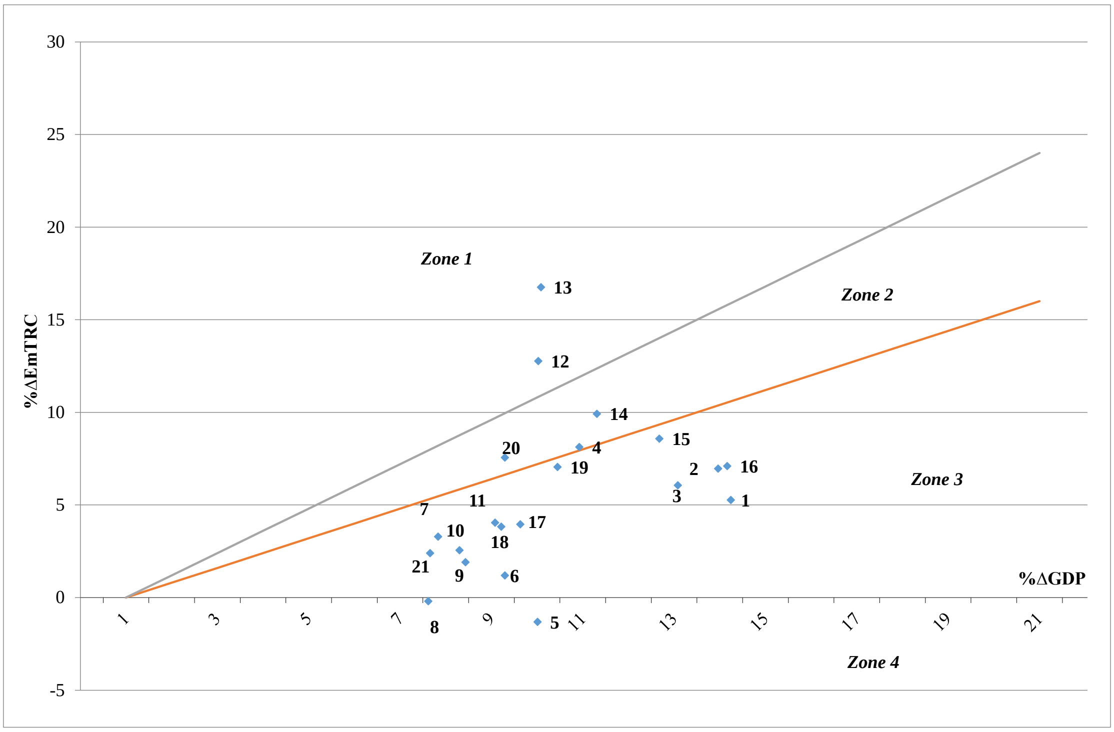

Fig. 7. Decoupling index between GDP and EmTRC in China. [Notes: the same as shown in Figure 3]

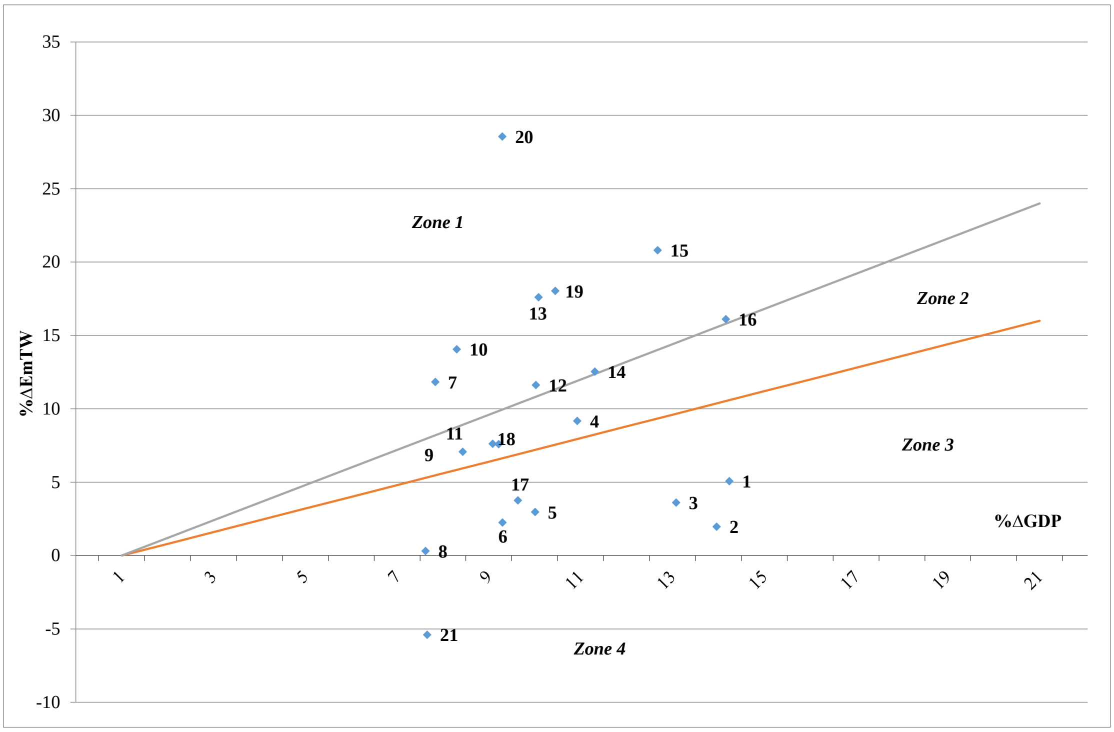

Fig. 8. Decoupling index between GDP and *EmTW* in China. [Notes: the same as shown in Figure 3]

Compared with resource use and specific pollutants, the decoupling condition of *EmTW* is even worse. Nine points were in the expansive negative decoupling area, four points were in expanding coupling area, and only eight points were in the decoupling area (Figure 8). The result indicates that China has worse decoupling performance of comprehensive environmental pressure induced by waste emission. The *EmTW* increased 6.6 times from 7.16×10^{23}sej in 1991 to 4.48×10^{24}sej in 2012 (Figure 9). Concerning on the components of *EmT*W, the emergy of solid waste (*EmSW*) contributed to a sharp drop which decreased from 3.85×10^{22}sej in 1991 to 1.64×10^{21}sej in 2012, but the emergy of waste water (*EmWW*) and waste gas (*EmWG*) contributed to a tremendous soaring, and *EmWW* and *EmWG* increased almost 2 and 8 times respectively compare to the level of 1991. Thus the waste gas is the most important contributor for the increasing of total waste emission, followed by the waste water, which suggests that China needs more rigorous regulations and specific policies to reduce the waste gas emission and waste water discharge in the future.

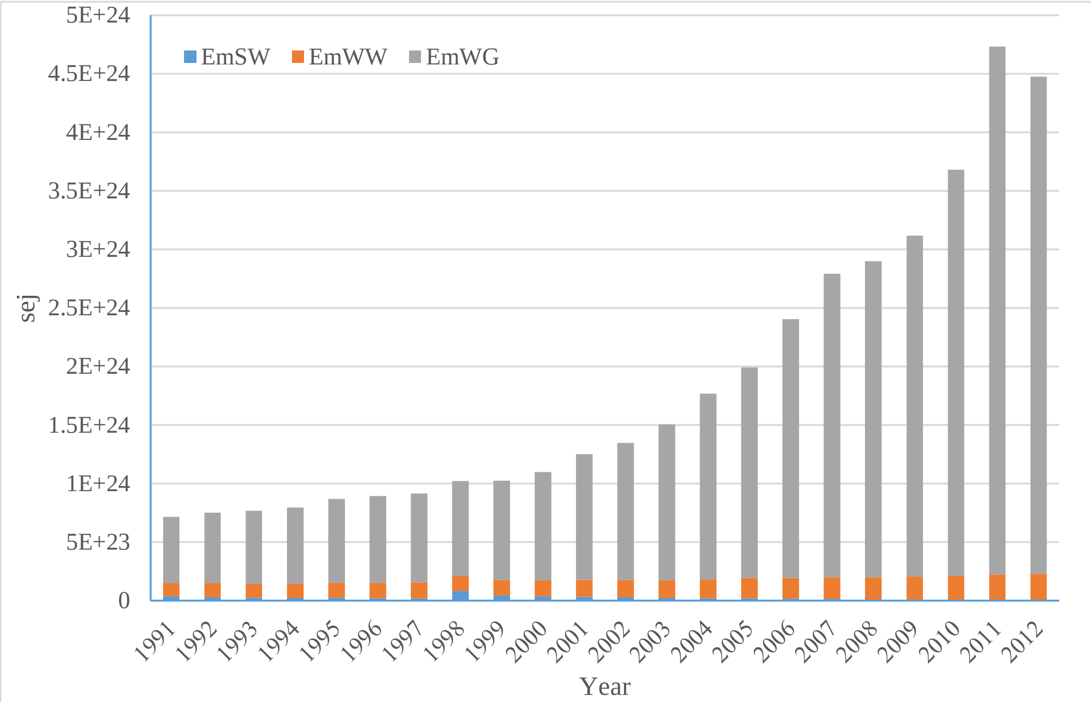

Fig. 9 The emergy structure of waste emission in China from 1991-2012

One of the main reasonsfor the worse decoupling performance of *EmTW*is that, unlike material flow based specific pollutant analysis which emphasizes the weight (quantities) of pollutants, emergy-based analysis can measure the varied qualities ofpollutants and reflect the relative contributions of various pollutants to the whole ecological economic system(Huang, Lee, 2006).The inconsistent of decoupling condition of *EmTW* with specific pollutants (waste water, SO_2 and solid waste) also indicates that the material flow based analysis alone will not adequately characterize the decoupling condition systematically.

Overall, for the specific source of environmental pressure, the decoupling performance of waste emission is better than energy consumption. One of the main reasons is that, unlike energy consumption, the volume of waste emission can be reduced by effective end-of-pipe treatment(Wang, Hashimoto, 2013). Another reason is that China has issued more stringent regulations and standards for emission reduction than energy saving. For example, China set mandatory total amount reduction targets for SO_2emission, but GDP intensity reduction target for energy consumption. However, for the aggregate level, the decoupling performance of waste emission (*EmTW*) is worse than resource use (*EmTRC*).

3.2 R/S Analysis of decoupling trend

From the above analysis, we can find that the trajectory of decoupling conditions from 1st period to 21st period has a characteristic of discontinuity and volatility. The time series of GDP elasticity of energy consumption, waste emission, *EmTRC* and *EmTW* during 1991-2012 also has the same characteristic (Figure 10) and the results of linear regression for all the time series is not significant (the column 2 and 3 in the Table 3) which means that we can't analyze dynamic trends of decoupling degree by using the method of linear regression analysis. In order to quantify the tendency and consistency of time series in Figure 10, the Hurst exponent, which was originally proposed by Hurst to analysis the time series flow data of Nile river, with theoretically improving by Mandelbrot and Wallis(Peng et al. , 2012)was adopted in this paper. R/S analysis, a fractal theory for time series research, which has been widely applied in geography, geology, climate change, economics and other fields, was the eldest and best-known method to estimate Hurst Exponent(Li et al. , 2011, Peng, Liu, 2012).The principle of R/S analysis and main calculation procedures of Hurst Exponent can be found in references (Granero et al. , 2008, Peng, Liu, 2012, Xu et al. , 2004).

The value of Hurst Exponent (H) ranges between 0 and 1. When the 0.5 < H < 1, it refers that the time series shows persistent or trend-reinforcing behavior (a positive correlation) which means the future trend oftime series will be consistent with the past, and the degree of persistent or trend-reinforcing depends on the extent for H's closeness to 1(Wang et al. , 2011). In our case, if the past decoupling degreehas been reduced (or increased), the degree in the futurewill also be reduced (or increased).The value ofH equals 0.5 which indicates that the time series iscompletely independent (there is no correlation between any element and a future element), and we cannotconclude whether the decoupling degree will reduce or increase. When the value of H ranges between 0 and 0.5, it indicates the time seriesshows anti-persistent behavior (a negative correlation) which means the future trendof time series will be opposite from the past. And the degree of anti-persistent depends on the extent for H's closeness to 0(Parmar and Bhardwaj, 2013, Weng et al. , 2008, Xu, Lu, 2004, Zhang et al. , 2013). In our case, if thepast decoupling degree hasareductive(or increase) trend, the decoupling degree of the future will assumethe increase (or reductive) trend.

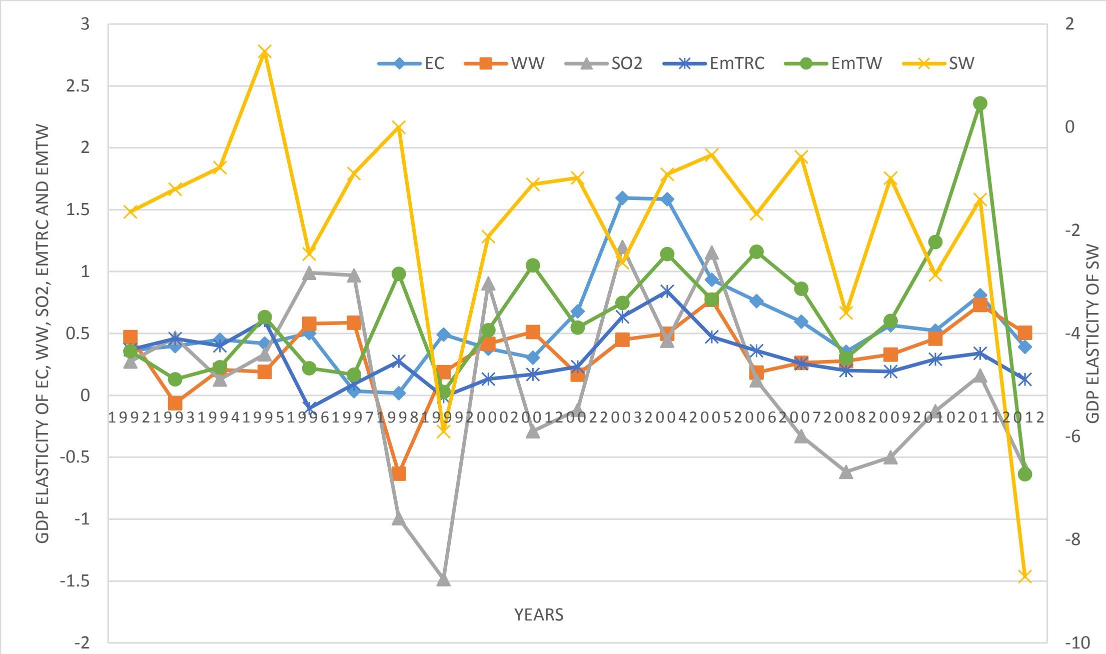

Fig.10. Evolution of GDP elasticity of energy consumption and waste emission. [Notes: Because the GDP elasticity of solid SW during 1997-1998 is 45.32, which is extremely higher than other periods, so the elasticity of 1997-1998 is not shown in the figure in order to observe the character of GDP elasticity of SW time series curve.]

The Hurst exponents of decoupling degree of energy consumption, waste emission, *EmTRC* and *EmTW*are shown in Table 3. The R^2 values (column 5 in Table 2) of all Hurst exponent estimations are greater than 85%, so the results of the estimation are significant. As for energy consumption, the Hurst exponent is 0.831, greater than 0.5 and close to 1, which means the decoupling degree of energy consumption during 1992-2011 isa persistent or positive correlation time series. In other words, the decoupling degree of energy consumption may behave a reinforcing decreasingtrend at slow speed (the coefficient is 0.0201) which indicates thatthe weakdecoupling conditionmay continue in the future. The Hurst exponent of decoupling degree of waste water, $SO_2$and solid waste is 0.541, 0.521 and 0.521 respectively, which greater than 0.5, refers that the decoupling degree of the waste emissions shows persistent or trend reinforcing behavior. But the reinforcing tendency is much weaker than energy consumption. Specifically, the decoupling degree of waste water shows weak decreasing trend and the decoupling degree of SO_2 and solid waste show weak increasing trend.

Refers to the environmental pressure at aggregate level, the Hurst exponents of *EmTRC* and *EmTW* are close to 1 which means that the decoupling degree of the two indicators both show a trend-reinforcing behavior. For the *EmTRC*, although the GDP elasticity may behave a reinforcing decreasing tread, the coefficient of regression equation is extremely small which means the decoupling performance may be stable in the future. But for the *EmTW*, the decoupling performance may be getting worse in the future.

Table 2

Hurst exponent of time series of decoupling degree in China from 1992-2011

y	Regression Equation	r^2	H	R^2
EC	y = 0.0201t + 0.357	0.097	0.825	0.998
WW	y = 0.0158t + 0.164	0.105	0.541	0.977
SO_2	y = -0.0291t + 0.421	0.063	0.521	0.861
SW	y = -0.1315t - 0.435	0.145	0.521	0.976
EmTRC	y = -0.0012t + 0.3149	0.001	0.818	0.980
EmTW	y = 0.0336t + 0.2699	0.120	0.814	0.979

Notes: the coefficient *t* represents time; r^2 is for the linear regression equation in column 2; R^2 is for the Hurt exponent estimation.

3.3 Cost Analysis of Decoupling

Generally speaking, in most developing countries, the improvement of resource efficiency and environmental quality mainly depends on the government investment, which was indicated as environmental protection investment (*EPI*) in statistical system. While for China, the comparable environmental protection investment has been increased from 1.7×10^{10}Yuan in 1991 to 6.59×10^{11}Yuan in 2011, almost increased 39 times. Concerning the cost of policy making, any efforts to environmental protection will not be cost-free economically, however, does the efforts of decoupling resource consumption and environmental pressure from economic growth pay a price in job growth for a country, and if so how much? Thus, one more index, local employment (*EPM*) was introduced as a basic information indicator (Table 3).

Table 3.

Environmental protection investments and employments in China

Indicators	Unit	1991	1996	2001	2006	2011
EPI	*Yuan*	1.7E+10	4.08E+10	1.11E+11	2.57E+11	6.59E+11
EPM	*Person*	6.55E+08	6.9E+08	7.28E+08	7.5E+08	7.64E+08

Notes: EPI indicates the environmental protection investment; EPM indicates the employment.

In order to measure the social cost for meeting sustainable decoupling in China, three more new cost-oriented indicators were applied, which are emergy based fix-year yield efficiency (*FYE*) (concerning most of master plan in economic, social and environmental area are five-years plan), invest cost for decoupling (*IfD*) and job-opportunities cost (*JfD*). The formulas for calculating above indicators in period 1991-1995 as follows:

$$FYE_{1991\text{-}1995}=(EmNRR_{1995}+EmECI_{1995}-EmNRR_{1990}-EmECI_{1990})/(RG_{1995}-RG_{1991}) \quad (2)$$

$$IfD=\Delta EPI_{1991\text{-}1995}/FYE_{1991\text{-}1995} \quad (3)$$

$$JfD=\Delta EMI_{1991\text{-}1995}/FYE_{1991\text{-}1995} \quad (4)$$

The formulas for calculating *IfD* and *JfD* in other four periods are same. The indicator of *FYE* is used for measuring the decoupling degree for each five-year period, *IfD*is used to evaluate the invest cost for decoupling of environmental pressures from economic growth, and *JfD* is used to measure the impact of decoupling on job-lost resulting from one sej/Yuan decoupling degree. The decoupling degree in each period is 6.64×10^{11}sej/Yuan, 1.59×10^{11}sej/Yuan, 7.95×10^{11}sej/Yuan and 3.46×10^{11}sej/Yuan. Meanwhile, the invest cost for achieve one unit sej/Yuan decoupling has increased from 0.029 Yuan in the period 1991-1995 to 0.363 Yuan in 1996-2000, then to 0.167Yuan in 2001-2005, and eventually to 1.239 Yuan in 2006-2010. As for job-opportunities cost, the job-lost resulted from 1 unite sej/Yuan decoupling increased from 4.08×10^{-5}Person in 1991-1995 to 1.89×10^{-4} Person in 1996-2000, then decreased to 2.42×10^{-5} Person in 2001-2005, and eventually decreasedto 3.42×10^{-5} Person in last period (Table 4).Overall, the investment cost of decoupling increased due to the increasing concerning about environmental problems and investment in environmental protection. On the contrary, the job-cost of decoupling decreased which indicates that the impact of decoupling on job-lost is negative at some extent, i.e., the decoupling of environmental pressure from economic growth creates job opportunities. Concerning on the impact of decoupling on the job-lost, the decoupling, which means the link between environmental pressure and economic growth has been broken, leads to the improvement of resource efficiency resulted from the application of advanced technologies and thus may result in job opportunities reduction. However, on the other hand, the decoupling process also encourages the development of environmental protection industries and thus creates new job opportunities (Zhang, Xue, 2014a). In our case, the effect of job creation is greater than the effect of job reduction.

Table 4.

Cost-oriented indicators for measuring sustainable decoupling in China

Indicators	Unit	1991-1995	1996-2000	2001-2005	2005-2010
Δ(EmNRR+EmECI)	*sej*	4.48E+23	1.26E+23	1.08E+24	8.36E+23

ΔRG	*capital*	7.10E+11	7.56E+11	1.41E+12	2.53E+12
ΔFYE	*Sej/Yuan*	6.31E+11	1.66E+11	7.66E+11	3.30E+11
ΔEPI	*Yuan*	1.85E+10	6.02E+10	1.28E+11	4.09E+11
ΔEPM	*Yuan*	2.57E+07	3.14E+07	1.85E+07	1.13E+07
IfD	*Yuan*	0.029	0.363	0.167	1.239
JfD	*Person*	4.08E-05	1.89E-04	2.42E-05	3.42E-05

4. Conclusion

The paper examined the decoupling conditions of particular sources of environmental pressure (such as energy consumption, waste water discharge, SO_2 and solid waste discharge) and aggregated environmental pressure indicated by emergy-related indicators from economic growth in China during 1991-2012, and further to analyze the evolutionary trend of decoupling degree by using R/S analysis method and the socio-economic cost of decoupling. Conclusions drawn from the paper are explained below.

During 1991-2011, greaterdecoupling performancein China can be found for waste emission than energy consumption from the perspective of specific environmental pressure analysis. The main reasons are that China has issued more stringent regulations and standards for waste emission reduction than energy saving and the end-of-pipe treatment is effective in emission reduction. In addition, the changes in decoupling performance at specific level also indicate that the decoupling condition can be influenced substantially by changes in environmental policies. On the contrary, from the aggregate level, the decoupling performance of waste emission is greater than resource use. The inconsistent results of decoupling analysis at specific level with aggregate level suggest that material flow based analysis along will not adequately characterize the decoupling condition, and emergy-based decoupling analysis may provide a new insight towards a better and comprehensive understanding of the decoupling of environmental pressures from economic growth.

The trend analysis at specific level indicate that the reinforcing tread of energy consumption is much stronger than waste emission. The weak decoupling condition may continue in the future for energy consumption and waste water discharge and the strong decoupling condition may also continue for SO_2 and solid waste. As for the analysis at aggregate level, the results indicate that the decoupling performance of resource use may be stable in the future, but the decoupling performance of the waste emission may be getting worse in the future which suggests that China needs more rigorous regulations and specific policies to reduce the waste emission, especially for the waste gas emission and waste water discharge. The current heavy atmosphere and water pollution in China has demonstrated that such policies should be made and implemented as soon as possible not only for the decoupling but also for the public health.

The investment cost of decoupling increased due to the increasing concerning about environmental problems and investment in environmental protection. On the contrary, the job-cost of decoupling decreased which indicates the decoupling process of environmental pressure from economic growth creates job opportunities because decoupling process could contribute to unleash the labor potential and industrial re-structure by developing the newenvironmental industries.

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